Thermal and acoustic properties of aluminium foams manufactured by the infiltration process

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A B S T R A C T

Metallic foams can be classified into closed-cell and open-cell foams depending on the connectivity between the cells. Currently, the majority of metallic foams on the market are closed-cell aluminium foams. However, open-cell aluminium foams are more appropriate for some applications. In this work, we analyze the thermal and acoustic properties, sound absorption coefficient at normal incidence and static flow resistivity of aluminium foams manufactured by means of the infiltration process. We have produced aluminium foams with similar porosity but with three different cell diameters: 0.5, 1 and 2 mm. The results reveal the important role of the cell diameter in fixing the physical properties of these materials. The foams manufactured by the infiltration technique are characterized by a highly homogeneous structure and by a high sound absorption coefficient at low frequencies when they are backed by an air gap. Specifically, its thermal and acoustic properties make the 0.5 mm cell diameter aluminium foam a good candidate for applications in the construction sector, for example.

1. Introduction

Conventional porous sound absorbers come in a variety of forms and their performance depends on their cell structure. The most common form of porous sound absorbers are fibrous materials and certain sorts of foams such as polymeric foams. In recent years, metallic foams have emerged as an attractive research field both from a scientific viewpoint and from the prospect of industrial applications, as well as for acoustic applications [1–6].

Regardless of their porosity, cell size and cell shape, there are two kinds of foams depending on the production methods: closed-cell and open-cell. Closed cells are surrounded by a wall of material and each cell is isolated and usually filled with gas, while open cells are connected to each other in space.

The majority of metallic foams on the market are closed-cell aluminium foams manufactured by various different processes. In some methods the liquid metal can be foamed directly by injecting a gas; in other techniques the foam is made by melting powder compacts containing the blowing agent [2,3,6]. In any case, the recent development of a variety of processes for producing these materials at a lower cost has increased their application in several fields such as automotive, aerospace and construction industries [1,3,4]. Metal foams are therefore a relatively new class of materials with low densities and novel thermal, mechanical and acoustic properties [7–12]. In particular, steel structures are often replaced by hybrids containing a high proportion of metal foams in lightweight design and construction. Significant weight reduction potential is achieved, thanks to the lower density produced by the cell structure of the material.

Due to their novelty and to the variety of processes for their production, metallic foams have not been studied to the same extent as other types of porous materials. In view of the recent upsurge in their use in contemporary technologies, it is advisable to have a complete characterization of these materials. In the present work we analyze the influence of cell structure on the thermal and acoustic properties of open-cell aluminium foams manufactured by the infiltration process. We present the experimental values of thermal conductivity, static flow resistivity and sound absorption coefficient at normal incidence. From the acoustic point of view, the foams have been compared to the commercial closed-cell foams known as Alporas. For the application of these materials, we sought answers to the questions of whether or not there is an optimized shape and cell, how to distribute cells with varying sizes, and how to choose the sample thickness and cavity depth behind the foam. We believe that the present work provides new information that may be very useful for the optimum design and optimization of these porous materials.

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2. Experimental

2.1. Manufacture of the aluminium foams

To manufacture the aluminium foams we used NaCl particles to make a preform that is removed by simply dissolving in water. Basically, the process consists of the three following steps:

(1) preparation of the preform in NaCl (common salt). The particle size of the NaCl must be selected according to the intended cell size of the final foam. In this case, the NaCl was sieved to obtain particles of a controlled size of 2.0 mm, 1.0 mm and 0.5 mm,
(2) infiltration of the preform with the liquid aluminium, under vacuum pressure and at a temperature of 700 °C. The aluminium matrix was an AlSiMg recycled alloy and
(3) the resulting Al/NaCl composites were machined into cylinders with measurements depending on the test, and the salt was removed by dissolving in distilled water, leaving the porous structure uncovered.

Fig. 1 shows the aluminium foams produced. The resulting cell structure of the metallic foam is a shape replication of the original NaCl particles. As previously reported in the literature, the structure of the aluminium foams was examined by optical and scanning electron microscope (SEM) [13,14]. A SEM image has been plotted in Fig. 2. The microstructural examinations reveal that the aluminium foams exhibit open cells which are uniformly distributed and well-interconnected. The porosities of the foams were determined using a pycnometer device. The aluminium foams have an average porosity ranging between 64% and 66% [13]. Thus the relative density $\frac{\rho^*}{\rho_S}$, defined as the density of the cell material divided by the density of the solid material forming the cell boundaries, varies between 36% and 34%.

2.2. Thermal conductivity

The thermal conductivity k of the aluminium foams was measured using a high insulating house of $400 \times 400 \times 400$ mm dimensions closed with a removable lid. The lid is insulated by a 5 cm thick Styrofoam plate, fixed to the angle pillars of the base rack with four screws. The base rack is also ground insulated through another 5 cm thick Styrofoam plate. The high insulation house has a large area, square aperture in each side wall of 210×210 mm. These apertures are closed by the measuring walls, in our case the aluminium foams, which are fixed in their positions by means of two tensioning screws. Each of these exterior walls carries a profile and a small eccentric plate to hold supplementary insulating material. Every angle pillar has a foam-insulated hole for insertion of a temperature probe into the house. The temperature inside the high insulating house was raised by means of a 100 W light bulb. Two diode sockets on the outer wall serve to connect a thermal regulation and the temperature probe supplied with it. The temperature switch is set on the fourth graduated division, thus producing in the steady state an internal temperature of about 50 °C.

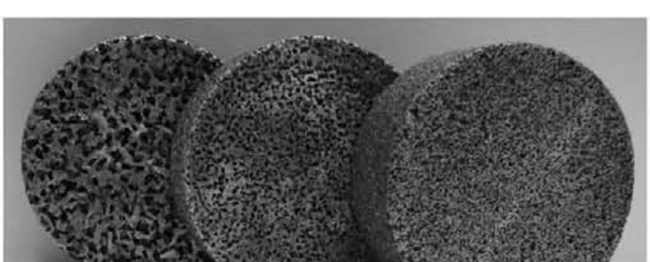

Fig. 1. Three aluminium foams with different cell sizes manufactured by means of the infiltration process.

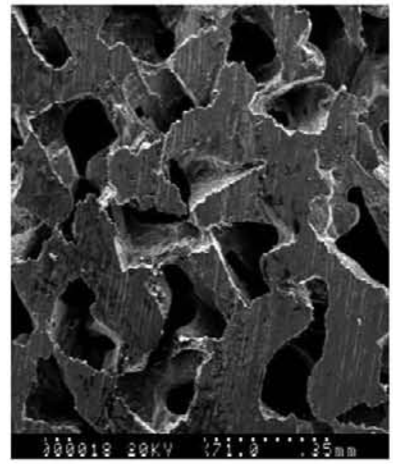

Fig. 2. SEM image of pores, interconnection, morphology and size.

The temperatures of the air inside and outside the house and on the internal and external walls of the aluminium foam were recorded by means of thermocouples inserted in the house across the holes in the corner posts of the house. The reading was taken when the thermocouples reached a constant value, to ensure that the system was near the steady state (5 h after the beginning of the measurement). The measurement method does not exactly follow the standard specifications; however, it is a reliable method with an uncertainty of less than 10%.

The phenomena participating in the transfer of heat through the layer are the conduction, convection and radiation. The light bulb of the high insulating house is placed inside a small black box to reduce the radiation effects. In this same line, the house allows the collocation of measuring walls until 5 cm thick. In general, the flux fraction transmitted by radiation, that in the case of parallel surfaces is independent on the distance between them, can be comparable to the flux transmitted by conduction (proportional to the inverse of the thickness of the sample) when the thickness of the measuring wall increases [15]. The thickness of the wall exerts a considerable influence especially in the case of bad heat conductors. Therefore, the thermal energy flow through a vertical, homogeneous, flat wall at moderate temperatures is mainly determined in the steady state (permanent state) by means of the air–wall heat transfer and the heat conduction in the wall [15].

Heat transfer by convection between internal air and internal wall of the aluminium foam:

$$\Phi = h_{\text{int}} \cdot S \cdot (t_1 - t_2) \tag{1}$$

where h_{int} is the convection coefficient of the interior air, S the wall area of the foam, t_1 and t_2 the temperature inside the box and of the internal wall of the aluminium foam respectively.

Heat transfer by conduction across the aluminium foam:

$$\Phi = k \cdot S \frac{(t_2 - t_3)}{d} \tag{2}$$

where k is the thermal conductivity, t_3 the temperature of the external wall of the aluminium foam and d the thickness of the aluminium foam and,

Heat transfer by convection between external wall of the aluminium foam and external air:

$$\Phi = h_{ext} \cdot S \cdot (t_3 - t_4) \quad (3)$$

where h_{ext} is the convection coefficient of the external air and t_4 the outer air temperature.

An experimental average value of the ratio $\frac{\Phi}{S}$ was estimated from expressions (1) and (3). Using this value, the k value was calculated using Eq. (2). For h_{int} and h_{ext} coefficients a value of 8.1 W/K m^2 was used as recommended by the manufacturer of the equipment [15] in the case of natural air movement in enclosed rooms.

2.3. Sound absorption coefficient at normal incidence

The sound absorption coefficient of an absorbing material depends on the frequency, the incidence angle of the sound, and on the way the material is mounted or installed. There are two main types of method for determining the absorption coefficient of acoustic materials: the reverberation time method for diffuse field; and the impedance tube method for normal incidence. The measurement in impedance tube is faster, and is often used in the first step of manufacturing a new material.

The absorption coefficient of the aluminium foams was measured in the impedance tube following standard ISO 10534-2:1998 [16]. The transfer function technique is based on the fact that the sound reflection factor at normal incidence, r, can be determined from the measured transfer function, H_{12}, between two microphones positioned in front of the material being tested [17]. We used a Model 4206 impedance tube with two Model 4186 B&K microphones and a 3560 °C Pulse Analyzer to process the signal using the Material Testing software. The Pulse Analyzer and a Pioneer A-305 R amplifier generated the signal at the impedance tube.

For the correct measurement of the sound absorption coefficient in the tube, the aluminium foams must have the exact diameter of the tube, without any air gaps that can alter the results [17,18]. This means that the mounting of the sample is a critical factor. The acoustic measurements for the frequency ranges below and above 1000 Hz were carried out separately in 100 and 29 mm diameter impedance tubes. The lower limit of the impedance tube is 50 Hz. Accordingly, the aluminium foams were machined to a diameter of either 100 or 29 mm and a thickness of 10, 20 and 45 mm. The sound absorption coefficient measured is the average of the measurement of three samples of the same characteristics. In order to check reproducibility, all measurements were performed on two different days. The foam sample was placed either directly against the back plate, with an air gap to the back plate in the impedance tube, and also combined with a mineral fibre.

2.4. Static airflow resistivity

Among the various parameters that may affect the acoustic performance of a porous material, it has been well established that static flow resistivity σ is one of the most important factors. The static airflow resistivity σ of metallic foams was measured by an experimental device designed in our laboratory following the standard specifications. This device mainly consists of an air supply system, a flow meter and a manometer. The digital manometer with a resolution of 0.1 Pa is used to measure the pressure drop of the airflow across the specimen after the flow has reached a steady stage. From the measured data in the laminar regime, the airflow resistivity σ is obtained as:

$$\sigma = \frac{\Delta P}{F} \frac{S}{d} \quad (4)$$

where ΔP is the pressure drop across the sample and F is the volume flow rate of air [19]. The foams used for the experiment were the samples machined to a diameter of 100 mm for the sound-absorption measurements. A number of readings are made at different flow rates to check whether the flow is in the laminar regime. The ratio $\frac{\Delta P}{F}$ has been calculated as the slope of the pressure drops ΔP versus F measured at the different flow rates.

3. Results and discussion

3.1. Open-cell aluminium foams

The values of the thermal conductivity k versus the cell diameter of the aluminium foams are shown in Table 1. The k values measured increase with the cell diameter. In the foams, k is a combination of the thermal conductivities of the aluminium and the air, so is strongly dependent on foam porosity. Also k is dependent on the aluminium matrix used for the foam fabrication. The heat transported by conduction in the solid is reduced by decreasing the volume fraction of the solid: when the cross sectional area of the solid is reduced the heat flow will encounter resistance. However, considering that the porosity is similar for all the samples tested, the cell diameter is the main parameter fixing the thermal behaviour of our aluminium foams. The smaller the cell dimensions, the higher the thermal resistance; therefore, as shown in Table 1 the effective conduction of the air decreases when the cell diameter decreases. Further reductions may also be possible if the cells have convoluted shapes.

Various works have been published in the literature on the modelling of thermal conductivity of different aluminium foams [20,21], but few data can be found related to its dependence on cell size. A theoretical work shows that k decreases if the cell size is reduced when the porosity is higher than 60%; while at low porosities cell size shows no significant effect on k [21].

With regard to acoustic properties, the σ values for the three pore sizes are also shown in Table 1: σ decreases when cell diameter increases. Sound is produced by vibrations in the air, so it is easy to imagine that sound cannot easily be propagated in materials through which air can pass with difficulty. Thus flow resistivity represents the difficulties of propagation of air in porous materials. The optimum value of this parameter must range between 5 and 10 kPa s/m^2 for insulation uses in construction [22]. Below 5 kPa s/m^2 the acoustic muffling is insufficient, and above 10 kPa s/m^2, the material is too compact and the sound propagation takes place mainly across the material. In any case, for materials preferably designed to fill cavities, a static flow resistivity of above 5 kPa s/m^2 is recommended. Few measurements of static flow resistivity have been found in the literature, and the majority corresponds to closed-cell aluminium foams, with σ values higher than the values measured in our foams [12].

The sound absorption coefficient at normal incidence was measured as a function of cell size and thickness in the frequency range between 100 Hz and 6500 Hz. As an example, Fig. 3 shows the absorption coefficient versus the cell diameter for the 20 mm thick aluminium foams: the 0.5 mm cell diameter aluminium foam exhibits the best absorption capacities. Also this aluminium foam presents the highest static flow resistivity value. It is clear that exits a dependence of α on the flow resistivity. Optimal values of the flow resistivity for an absorber layer have been generally derived from model theories of absorbers. Mechel [23] postulated that: (1) the answer is depending on the criterion used for the optimum and (2) the geometrical and material variables defining the absorbing characteristics of an absorber could be expressed by one non-dimensional parameter. In this line, a possible criterion for an optimal absorber based on the open cell aluminium foams can be that the absorption coefficient may reach values higher than a given limit at the lowest possible frequency and/or at a smallest possible layer thickness. For a simple layer for a limit value of α of 0.9

Table 1
Thermal conductivity and static flow resistivity versus cell size of the aluminium foam fabricated.

Cell size of Al foam (mm)	Thermal conductivity k (W/K m)	Static flow resistivity σ (Pa s/m^2)
0.5	0.6	1.2×10^4
1	1.1	4.0×10^3
2	3	1.5×10^3

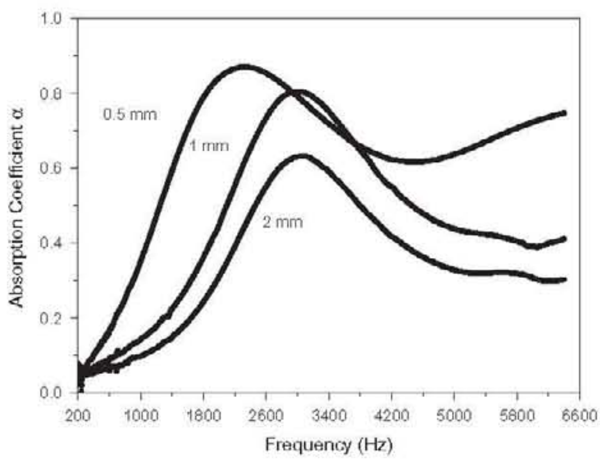

Fig. 3. Sound absorption coefficient at normal incidence for 20 mm thick aluminium foams. The cell size value is indicated on the corresponding absorption coefficient curve.

Table 2
Position of the maximum absorption peak as function of the cell size for different thickness of the aluminium foam.

Thickness (mm)	Position of the maximum absorption peak (Hz) pore size		
	0.5 mm	1 mm	2 mm
10	4500	6030	6160
20	2298	3080	3214
25	1600	–	–
45	931	1100	1451

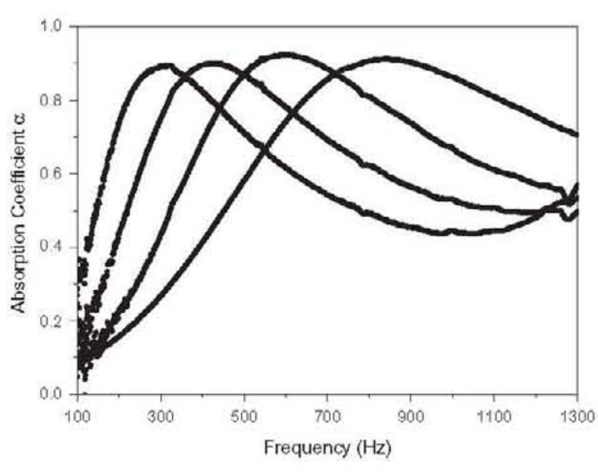

Fig. 4. Sound absorption coefficient for a 45 mm thick aluminium foam with a cell size of 0.5 mm backed by an air gap of 2, 5 and 10 cm. The thickness of the air gap is indicated on the curve.

at normal incidence this occurs when $\sigma d = 2Z_0$ where Z_0 is the air impedance. Following this expression, the higher the flow resistivity value is the smaller the thickness of the aluminium foam to behave as infinitely thick with respect to absorption. In particular, a d value of around 65 mm fulfils the above condition for the aluminium foam of 0.5 mm of cell diameter.

Again, taking into account the aluminium foams present a similar porosity, the different sound absorption behaviour can be attributed to the effect of the cell diameter. The sound absorption in porous materials is considered to be mainly due to the consumption of the sound energy by the viscosity and to thermal conduction when the sound is propagating into a thin tube. The sound wave penetrates the material and once inside, the amplitude of vibration of the air molecules is progressively damped due to friction with the cavity surfaces. If the cavities have a small diameter, this leads to a greater resistance and hence to greater dissipation of the sound wave, ultimately resulting in greater sound absorption. Simulations carried out by Lu et al. on porous metals with cell sizes between 0.5 and 5 mm showed that the contribution of the viscous effect rises with increasing frequency and decreasing cell size [24]. The overall sound absorption coefficient appears to be largely dependent on the contribution of the viscous effect. Thus the good acoustic behaviour observed in samples with smaller cells may be associated specifically with the phenomenon of internal vibration of the sound wave. Increasing the thickness of the foam increases its absorption capacity: a high thickness means a larger surface area over which the air passes with friction, so the influence of viscosity is increased. The maximum absorption peak position is also displaced at low frequencies. In Table 2 it has been summarized the position of the maximum absorption peak as a function of thickness for the three cell sizes.

From the data shown in Fig. 3 and Table 2 it can be deduced that the aluminium foams – in common with all rigid-framed porous materials in general – have low absorption at low frequencies if they are backed directly by a rigid surface. In order to enhance the sound absorption in the low frequency range, an air gap between the face of the material and the rigid surface is effective. The introduction of an air gap is common practice in construction in order to improve the acoustic or thermal properties of the constructive system. In Fig. 4 the absorption curves corresponding to a 0.5 mm cell diameter foam were plotted for three different air gap thicknesses. The displacement of the maximum absorption peak depends on the thickness of the air gap. In particular, it is important to notice the displacement of the position of the maximum absorption peak at frequencies down to 300 Hz when the air gap is of a thickness of 10 cm.

The viscous and thermal losses are the principal sound dissipation mechanisms when the open-cell foams are backed directly by a rigid surface. When they are backed by an air-gap the predominant mechanism appears to be the Helmholtz resonant absorption. A Helmholtz resonator is composed of a cavity with a small neck and has a definite absorption peak at the resonant frequency f_r that can be calculated by [25]:

$$f_r = \frac{c}{2\pi}\sqrt{\frac{A}{LV}} \quad (5)$$

where c is the speed of sound, A the cross-sectional area of the neck, L the neck length plus $0.8\sqrt{A}$ and V the volume of the cavity. In the present open-cell aluminium foams, the combination of each cell channel with the backing air gap can be regarded as a Helmholtz resonator, with the channel as the neck and the air gap as the cavity. Some examples of the resonant frequency values measured and estimated by Eq. (5) have been summarized in Table 3. The value of the absorption coefficient at this position is also indicated. The minor discrepancies observed may be due to the existence of numerous air channels of different lengths in the foam. Therefore the position of the absorptive peak extends to a broader peak, due to the large number of differently-dimensioned Helmholtz resonators.

Table 3
Measured and estimated values calculated by expression (5) of the resonant frequency. The values of the absorption coefficient at the maximum peak are also shown in the table.

Al foam thickness (mm)	Al foam cell size (mm)	Air gap thickness (cm)	Absorption peak at normal incidence	Peak position measured (Hz)	Peak position calculated (Hz)
45	2	5	0.80	571	540
10	1	2	0.74	1600	1594
45	1	10	0.99	333	319
45	0.5	10	0.90	290	250
45	0.5	5	0.90	400	340
45	0.5	2	0.92	580	540

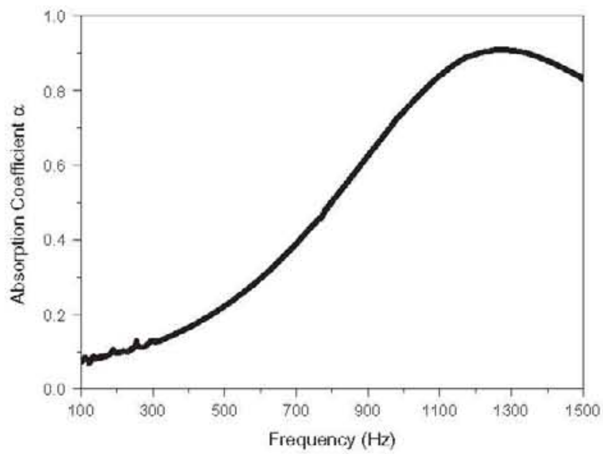

Fig. 5. Sound absorption coefficient at normal incidence of 45 mm thick aluminium foam combining 2 mm and 4 mm cell diameters.

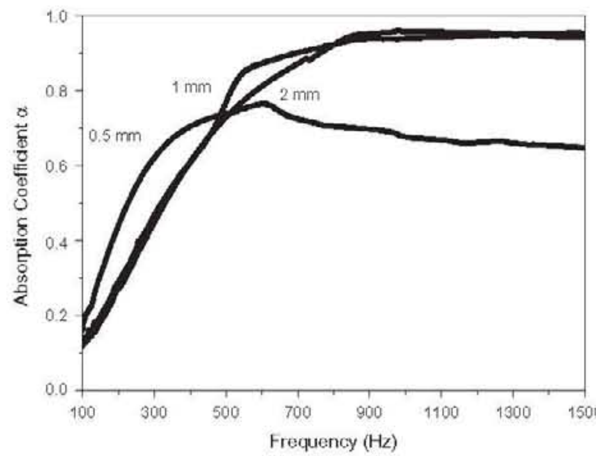

Fig. 6. Sound absorption coefficient at normal incidence of the structure consisting of a 10 mm thick aluminium foam combined with a 20 mm thick mineral fibre. The absorption coefficient measured for this configuration (aluminium foam + mineral fibre) has been plotted for the three cell diameters.

This behaviour suggests the possibility of using these aluminium foams as selective low-frequency absorptive systems: the resonant frequency of the resonator depends on the air gap selected. Another possible method of modifying the resonant frequency position is to combine two different cell sizes in a consecutive way in the same foam. This combination can also be regarded as a Helmholtz resonator, with the small cell size channel as the neck and the high diameter cell channel as the cavity. This kind of structure can be produced by means of the infiltration process [10]. An example is shown in Fig. 5; this foam combines a 2 and 4 mm cell diameter. The peak position of the 2 mm cell diameter foam of the same thickness is around to 1500 Hz.

Using aluminium foam with a mineral fibre is another way of increasing the low frequency absorption of the foam. Fig. 6 shows the absorption coefficient measured for a 10 mm thick foam combined with a 20 mm thick mineral fibre. Each curve corresponds to a cell diameter. Mineral fibres, made of twisted filaments, are known to be good sound absorption and thermal insulation materials. However, they have low mechanical strength, so aluminium foam can give the structure rigidity. On the other hand, the effect of the mineral fibre is to raise the maximum absorption peak of the foam with a displacement at low frequencies. An increase in the absorption of the aluminium foam at high frequencies is also observed: a general characteristic of the acoustic behaviour of aluminium foams is the decrease in absorption capacity above the frequency of the maximum absorption peak. According to these results, low corrosion and easy cleaning properties of aluminium could make these foams suitable with mineral fibre compositions useful for internal spaces to control the reverberation time.

3.2. Comparison with closed-cell aluminium foams

Previously, we have analyzed the acoustic behaviour of two types of closed-cell aluminium foams: the commercial Alporas and foams manufactured using the powder metallurgy technique [26]. These aluminium foams have been characterized in the same impedance tube and following the same measurement routine that the open cell aluminium foams fabricated by the infiltration process. In Fig. 7 we have plotted together the sound absorption coefficient at normal incidence of the open-cell foam that present the best sound absorption properties (0.5 mm cell size) and an Alpora of the same thickness. The open-cell aluminium foam shows a broad absorption peak situated at lower frequencies.

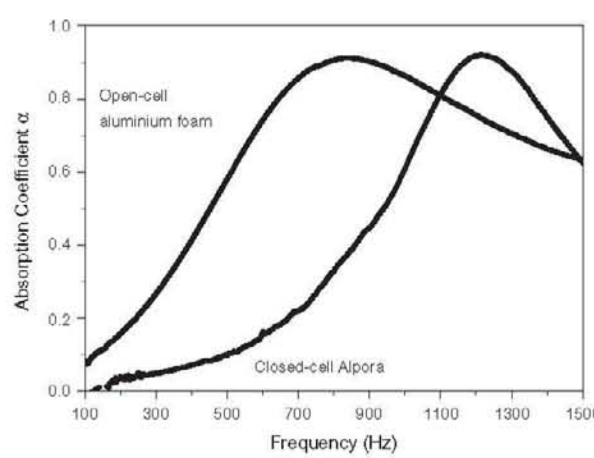

Fig. 7. Sound absorption coefficient of closed- and open-cell aluminium foams at normal incidence. The thickness of the foams is 45 mm.

The improvement of the absorptive properties of aluminium foams was also compared when they are backed by an air cavity.

Table 4
Frequency position of the maximum absorption peak for the different types of aluminium foams without air gap and combined with an air cavity of 2.5 and 10 cm.

Aluminium foam	0 cm (Hz)	2 cm (Hz)	5 cm (Hz)	10 cm (Hz)
Infiltration process	–	1365	820	413
Alporas	3564	1350	759	473
Powder metallurgy process	4800	1964	1134	638

To perform this experiment, the thickness of the closed-cell aluminium foams manufactured by means of powder metallurgy has to be reduced to 5–10 mm to guarantee that some of the cells go through the foams [26]. The drawback of these aluminium foams is that their structure is highly non-homogeneous and difficult to reproduce during the manufacturing process.

In Table 4 the position of the maximum absorption peak for the three aluminium foam types is shown as a function of the air-gap thickness. As we have previously explained, the Helmholtz resonator is the mechanism which explains the behaviour of the aluminium foams manufactured by the infiltration process and the powder metallurgy technique. The behaviour of the closed-cell Alporas can be represented for a system consisting of two layers separated by an air gap, whose maximum absorption peak position is well calculated by means of the expression

$$f = 60\sqrt{\frac{1}{t}\left(\frac{1}{m_1}+\frac{1}{m_2}\right)} \tag{6}$$

where t is the thickness of the air gap, and m_1 and m_2 are the density per unit of surface for each one of the layers [27]. When the air gap is filled with a porous material, as for example a mineral fibre, this frequency is displaced to lower values. In the calculus of this resonance frequency an appropriate model for the porous material has to be considered [19].

Therefore, manufactured aluminium foams present good acoustic behaviour, comparable to other commercially-produced foams such as Alporas. They have a very homogeneous structure combined with a low-cost production process that makes it easy to manufacture aluminium foams with different cell sizes and hence with different thermal and acoustic properties.

4. Conclusions

We have analyzed the thermal and acoustic behaviour of open-cell aluminium foams manufactured by the infiltration process. These foams offer the advantage of having a low manufacturing cost and a very homogeneous structure. Furthermore, the use of recycled aluminium gives a more economical process without causing any detrimental effect on its physical properties.

The measurements of thermal conductivity, static flow resistivity and absorption coefficient at normal incidence in aluminium foams of similar porosity have served to reveal the importance of cell diameter in determining their properties.

The examination of the acoustic performance of aluminium foams has shown that this material possesses considerable potential for application as a sound absorber. The sound dissipation mechanisms in open-cell foams are principally viscous and thermal losses when there is no air-gap backing, and predominantly Helmholtz resonant absorption when there is an air-gap backing.

We present a comparative analysis with commercial aluminium foams. This shows that manufactured aluminium foam may be a competitive candidate for noise control applications in different sectors, including the construction sector. Aluminium foams offer a novel aesthetic that together with their sound absorption and insulating capacities and their corrosion resistance have led to the use of these materials in roofs and walls in different kinds of construction. Moreover, we are starting to see the façades of some modern buildings decorated with different lightweight rigid panels manufactured with aluminium foam. In practical applications, however, other properties such as the durability and fire resistance of these materials have also been considered.

Another advantage of these materials compared to other acoustic materials such as polyester and glass fibre is that aluminium foam is eco-friendly and 100% recyclable, while the other two materials are not easy to recycle.

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